

Use of New Industrial Coatings for the U.S. Navy Waterfront Structures

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Abstract

The U.S. Navy has been utilizing epoxy polyamide and coal tar epoxy coatings to protect waterfront structures such as piers and wharfs for many years. However, these particular coatings have become undesirable for use as their VOC levels exceed the newly instituted guidelines published by the EPA in 1999. Therefore, the Navy has begun the process of researching other potential coatings which meet the current federal standards. Some of these coatings include fusion bonded epoxy coatings, moisture cured urethane coatings, epoxy aliphatic polyurethane with polypropylene fiber coatings, and glass flake resin coatings. Some preliminary testing suggests that fusion bonded epoxy and moisture cured urethane coatings provide adequate corrosion resistant properties in the harsh marine environment. However, more standardized testing must be instituted for these potential coating systems in order to ensure the Navy makes the most informed decision in the future.

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1-Introduction

1.1-Current Navy Practice

Corrosion of facilities in close proximity to the shore or waterfront (which includes piers, steel piles, mooring structures, and fuel lines) is a serious problem that has faced the United States Navy since its inception. In 1992, the Navy (1) estimated the direct costs associated with corrosion exceeded \$70 million dollars each year. Since these facilities provide the major support to the fleet and its mission, these facilities must be protected by the most effective corrosion prevention system with the limited funding constraints to ensure that continuing support can be provided.

In order to provide this needed protection, the Navy has utilized two particular types of coatings. They are epoxy polyamide and coal tar epoxy. According to the American Institute of Steel Construction, "Epoxy polyamide paints are the most popular of all epoxy binders for use on structural steel. When exposed to weathering, they chalk quickly, but retain excellent chemical and abrasion resistant properties."¹ In addition, the United States Army Corps of Engineers state "Coal tar epoxy coatings have good impact and abrasion resistance. As with most epoxy coatings, they provide good long-term protection in immersion because of their excellent barrier properties."² While the performance of these coatings has been adequate for the task, there are new environmental concerns with these particular coatings. Specifically, the Volatile Organic Content (VOC) of these coatings has been questioned due to the toxicity of some organic components in these substances. Specifically, the United States Army Corps of Engineers state "The adopted threshold limit value for coal tar pitch volatiles is a low 0.2 mg/cm³ expressed as a time weighted average (American Conference of Governmental Industrial Hygienists, 1989-1990). Coal tar pitch volatiles are a confirmed human carcinogen as well."³

1.2-New Guidelines

In response to the rising concern of air pollution, the Environmental Protection Agency (EPA) established new federal standards for VOC limits of architectural coatings. The EPA defines a VOC as "any organic compound that participates in atmospheric photochemical reactions, that is, any organic compound other than those which the Administrator designates as having negligible photochemical reactivity..."⁴ A list of the chemicals, which are considered to possess negligible photochemical reactivity, is contained in 40 CFR 51.100(s). These new standards were promulgated under the Code of Federal Regulations (CFR), specifically 49 CFR Part 59, subpart D, 63 FR 48848 on September 11, 1998. Subsequent to the submission of comments by industry representatives and other interested parties, the final rule with all applicable corrections and amendments was issued under 40 CFR Part 59, subpart D, 64 FR 34997 on June 30, 1999.

These new EPA guidelines (2), which were developed pursuant to section 183(e) of the Clean Air Act, were the product of a study performed by the EPA under the authority of the same section. The study was conducted to determine the specific level of VOC emissions from the commercially available products in the industry. The EPA

study concluded “the architectural coatings category accounts for about 9 percent of the emissions from all consumer and commercial products. It is one of the largest emission sources among the consumer and commercial products categories and in many States represents one of the largest identifiable sources of unregulated VOC emissions.”⁵ These emissions react with oxides of nitrogen (NO_x) to produce ground level ozone, which significantly contributes to smog. According to the EPA, “exposure to ground-level ozone is associated with a wide variety of human health effects, agricultural crop loss, and damage to forests and ecosystems...The acute health effects include respiratory symptoms, effects on exercise performance, increased airway responsiveness, increased susceptibility to respiratory infection, increased hospital admissions and emergency room visits, and pulmonary inflammation...Available information also suggests that long-term exposures to ozone may cause chronic health effects (e.g. structural damage to lung tissue and accelerated decline in baseline lung function).”⁶ The EPA concluded that “VOC emissions from the use of architectural coatings have the potential to cause or contribute to ozone levels that violate the national ambient air quality standards (NAAQS) for ozone.”⁷

Subsequent to the study and the conclusions, the new standards were enacted to reduce the total amount VOC emissions. Specifically, the EPA concluded that “the final rule is estimated to reduce VOC emissions by 103,000 megagrams per year (Mg/yr) (113,500 tons per year [tpy]).”⁸

As this new federal standard is applicable to numerous types of commercially available architectural coatings, the particular group for the Navy’s waterfront coatings must be determined in order to identify the VOC limit. After reviewing the various definitions of each coating type within the EPA’s documentation, the waterfront coatings were placed in the industrial maintenance coating category. The EPA’s definition was “a high performance architectural coating including primers, sealers, undercoaters, intermediate coats, and topcoats formulated and recommended for application to substrates exposed to one or more of the following extreme environmental conditions in an industrial, commercial, or institutional setting: immersion in water, wastewater, or chemical solutions (aqueous and nonaqueous solutions), or chronic exposure of interior surfaces to moisture condensation; acute or chronic exposure to corrosive, caustic, or acidic agents, or to chemicals, chemical fumes, or chemical mixtures or solutions; repeated exposure to temperatures above 120 °C (250°F); repeated (frequent) heavy abrasion, including mechanical wear and repeated (frequent) scrubbing with industrial solvents, cleansers, or scouring agents; or exterior exposure of metal structures and structural components.”⁹ The VOC limit for the industrial maintenance coating category is 450 grams per liter (3.8 pounds per gallon).

1.3-Potential Solutions

In general, the Navy (*1*) has identified four distinct methods to prevent corrosion of their fleet of ships and numerous shore facilities, which includes their piers and wharfs. The first one is the selection of specific materials, such as stainless steel, to prevent this corrosion due to their desirable qualities in a given environment. The Navy states that “Corrosion resistance as well as strength, ductility, fabricability, availability, and cost are all factors that must be considered in selecting a material.”¹⁰ The next

potential solution is to utilize a cathodic protection system to disrupt the mechanisms that continue to feed the corrosive nature of a given system. According to the Navy, “there are two basic methods of supplying the electrical currents required to interfere with the electrochemical cell action. The first method uses the corrosion of an active metal, such as magnesium or zinc, to provide the required electrical current. In this method, called sacrificial or galvanic anode cathodic protection, the active metal is consumed in the process of protecting the surfaces where corrosion is controlled and the anodes must be periodically replaced. In the second method, an alternative source of direct electrical current, usually a rectifier that converts alternating current to direct current, is used to provide the required electrical current. In this system, the electrical circuit is completed through an inert anode material that is not consumed in the process.”¹¹ The third option involves changes made to the environment in order to mitigate the corrosive nature. The last option is the application of a protective coating to the surface that needs protection. This coating serves as a barrier between the structural member and the environment.

Due to the many competing needs for funding in the Navy and the relatively inexpensive nature of coatings when compared to other potential solutions, the Navy has typically utilized coatings to provide protection to their pier-side structures in lieu of the other options. Due to the increasing concern regarding the VOC emissions of the epoxy polyamide and coal tar epoxy coatings, the Navy has chosen to investigate the possibilities of using some relatively new coating technologies. These coating technologies include fusion bonded epoxy (FBE) coatings, moisture cured urethane (MCU) coatings, epoxy aliphatic polyurethane with polypropylene fiber coatings, and glass flake resin coatings.

1.4-Fundamentals of Coatings

Before the specific coatings mentioned above are described, it is necessary to elaborate on the three basic components of a coating and the three basic curing processes. The Navy (*I*) states that each component of a coating can be classified as a solvent, resin, or pigment. “The solvent is used to dissolve the resin material that actually forms the coating film. It also reduces the viscosity of the product to permit easier application as well as affecting its leveling, drying, durability, an adhesion...The resin is the binder or film-forming part of the coating that is responsible for most of the properties of the coating...The chief function of the pigment is to provide opacity (hiding) to protect the organic vehicle from degradation by sunlight. Pigments also provide color, improve adhesion and weather resistance, decrease moisture permeability, and control gloss.”¹² Additionally, there are additives, which are considered either pigments or resins, that can be placed in the coating mixture to improve the any of the qualities.

The Navy (*I*) describes that the three basic curing processes for a given coating consist of: air oxidation of drying oils, solvent or water evaporation, or a chemical reaction of components. Air oxidation of drying oils consists of “oxygen from the air reacting with the unsaturated fatty acids in their drying oils. By this reaction, liquid resins are converted to a solid film.”¹³ The solvent or water evaporation curing method simply consists of the dissolved resin being deposited on the given surface once the solvent has fully evaporated. The rate of evaporation depends on the given solvent (water, petroleum based, etc.) and specific atmospheric conditions when the coating is

applied. The last curing process involves the chemical reaction of two specific components. These components “are generally packaged in two separate containers and mixed to initiate the reaction. Components must be combined in the specified proportions in the manner specified by the supplier to achieve a complete reaction. Sometimes, an “induction period” is required after mixing and before application to permit the reaction to get started. After mixing, there is always a “pot life” during which the coating must be applied, before the reaction has advanced so far as not to permit proper application and curing.”¹⁴

2-Fusion Bonded Epoxy Coatings

2.1-Background

Since the inception of their use in the 1960's, fusion bonded epoxy coatings (3), or FBE coatings, have introduced a valuable new alternative for industrial protective coatings. As the name implies, a chemical reaction is needed between the main constituent parts in order to adhere the coating system to the metal substrate underneath. This chemical reaction, which is termed cross-linking, prevents the individual components from any significant movement after the reaction has occurred. Since this chemical reaction is irreversible, the FBE coating is called a thermoset polymer coating.

The two major components of the FBE coating system (3) are the resin and hardener, which are stored separately in a dry powder form. The typical resins utilized for FBE coatings are derivatives of bisphenol A and epichlorohydrin. The typical hardeners, or curing agents, include dicyandiamide, aromatic amines, and aliphatic diamines. These two primary parts, which are applied to a surface in a temperature range of 360°F to 480°F, will form a liquid substance that can easily be applied. The most common methods to heat the metal substrate for application are “induction heating” or “oven heating.” Induction heating is the use of “a high frequency alternating current magnetic field, which heats the metal part to the required temperature.”¹⁵ The FBE is converted into its liquid form on a “fluidization bed.” “In a fluidization bed, the powder particles are suspended in a stream of air, in which the powder will behave like a fluid. Once the air supply is turned off, the powder will remain in its original form. The fluidized powder is sprayed onto the hot substrate using suitable spray guns. An electrostatic spray gun incorporates an ionizer electrode on it, which gives the powder particles a positive electric charge. The steel to be coated is “grounded” through the conveyor. The charged powder particles uniform wraps around the substrate, and melts into a liquid form...Standard coating thickness range of stand-alone FBE coatings is between 250 and 500 micrometers (10 to 20 mils).”¹⁶ Some of the additional components include pigments and other additives to produce the required qualities, such as color or permeability, for a given application of the coating. The primary advantage of this coating system includes a very quick curing time, which ranges from only seconds to a few minutes. Other advantages “over conventional liquid coating application are ease of application, less waste of material, and rapid application.”¹⁷

Some of typical commercial uses for this product include the coating of rebar in the construction of concrete structures utilized in the transportation industry due to the high chloride content, which can create very corrosive environments at high

concentrations, on the road surfaces. In addition, this product is utilized as a coating for the interior and exterior of piping systems, which either are located in harsh environments or are transporting substances with highly corrosive properties.

2.2-Performance

The United States Army Corps of Engineers (4) identified in 1995 the same concerns regarding the toxicity of coal tar epoxy and epoxy polyamide coatings in use at the time. Therefore, they performed testing on six samples of hot-rolled commercial grade carbon steel, which measured 3 in. by 9 in. by 0.125 in., utilizing four independently chosen FBE coatings and two control coatings to ascertain if the new coating system was a viable alternative. In order to provide direct comparison of the results for the current and potential new coating systems, the two control coatings were the coal tar epoxy and epoxy polyamide coatings. The six carbon steel test samples were independently prepared in accordance with Steel Structures Painting Council (SSPC) Surface Preparation (SP) specifications SP 1 and SP 5 prior to shipment to the application site. The manufacturer's recommended practice was utilized for application of these four coatings.

Subsequent to the preparation of these samples, the Corps of Engineers' Construction Engineering Research Laboratories (4) performed four separate tests. These tests included salt and fresh water immersion, cyclic corrosion weathering, cathodic disbondment, and impact resistance. These particular tests were chosen because they most closely approximate the typical environmental conditions for the steel pile structures. All performed testing and evaluation procedures were accomplished in accordance with the published ASTM standards at that time. The immersion test consisted of two identical testing sets, one set with synthetic sea water and one with fresh water. The testing included constant exposure of a previously scribed sample to the specific water environment for a total of 112 days. The degree of rusting and blistering was determined after 7, 60, and 112 days and for undercutting after 112 days. The weathering test involved the exposure of the previously scribed sample to one week of ultraviolet (UV) light, specifically UV-A lamps, for one continuous week. Subsequent to that one week of UV light exposure, the samples were subjected to one continuous week in a salt spray cabinet. The degree of rusting and blistering was concluded after 2, 4, 8, 12, and 14 weeks and for undercutting after 14 weeks. The cathodic disbondment test "was used to measure the susceptibility to corrosion at holidays and other film defects in a highly conductive electrolyte. Three tests were conducted on each of the FBE and control coatings."¹⁸ Finally, the all coating systems were tested to determine their resistance to an impact which might occur during shipment or installation. The first three tests were conducted to closely simulate the typical environment for a pile installed in a marine environment. This final test was accomplished to simulate the expected conditions under which the pile would be installed at a given construction site.

After conducting the synthetic sea water immersion tests, Table 1 was generated to summarize the results (4). System No. 6, which was the coal tar epoxy coating, received a perfect cumulative (composite) score of 30, which means that there was no visible evidence of degradation in the coating. The FBE A, B, and C coatings received cumulative scores of 28, 27.3, and 29.3 respectively, which indicate only a minimal

amount of deterioration. However, the FBE coatings exhibited reduced performance in the undercutting category at the conclusion of the testing period, which can lead to long term performance concerns if the coating is significantly damaged during installation. Finally, the FBE D coating received the worst score of the group, which indicates a poor level of performance. Subsequent to the fresh water immersion tests, Table 2 was

Table 1. Synthetic Sea Water Immersion Test Results (4).

Coating System	7 days Rusting/Blistering	60 days Rusting/Blistering	112 days Rust/Blister/ Undercut/Composite
System No. 6	10/10	10/10	10/10/10/30
System No. 21	10/10	10/6	10/4/8.5/22.5
FBE-A	10/10	10/10	10/10/8/28
FBE-B	10/10	10/10	10/10/7.3/27.3
FBE-C	10/10	10/10	10/10/9.3/29.3
FBE-D	10/10	10/5	10/3.3/5.7/19

constructed (4). After reviewing the results, the epoxy polyamide, or system No. 21, exhibited no degradation in the coating system while the coal tar epoxy did not perform as well when compared to the other coatings. While the FBE A, B, and C coatings performed slightly better in the fresh water as evidenced by an overall increase in the cumulative score from the previous test, the coatings still exhibit a small amount of undercutting. Overall, the epoxy polyamide and FBE A, B, and C coatings provided excellent protection in the environment. Again, the FBE D coating performed the worst of the group in this test.

Table 2. Fresh Water Immersion Test Results (4).

Coating System	7 days Rusting/Blistering	60 days Rusting/Blistering	112 days Rust/Blister/ Undercut/Composite
System No. 6	10/10	10/6.5	10/5.5/9.5/25
System No. 21	10/10	10/10	10/10/10/30
FBE-A	10/10	10/10	10/10/9.5/29.5
FBE-B	10/10	10/10	10/10/8.8/28.8
FBE-C	10/10	10/10	10/10/9/29
FBE-D	10/10	10/10	10/5.6/5.5/21

Table 3 summarizes the results (4) of the cyclic corrosion testing, which was intended to simulate the normal atmospheric attack on the coating system in a marine

environment. The coal tar epoxy coating, with a cumulative score of 25.1, performed the best and exhibited the smallest amount of undercutting. The next two coatings, with respect to ranking, are the FBE A and C coatings. However, the overall performance of these two FBE coatings is only fair as the degree of undercutting was significant during the testing period. In addition, the epoxy polyamide coating and the other two FBE coatings exhibited a significant amount of blistering, which began as early as two weeks for the FBE D coating, as well as significant undercutting. The FBE D coating, which only received a cumulative score of 12, performed very poorly during this test.

Table 3. Cyclic Corrosion Test Results (4).

Coating System	Rusting/Blistering				Rust/Blister/ Undercut/Composite 14 weeks
	2 weeks	4 weeks	8 weeks	12 weeks	
System No. 6	10/10	10/10	10/10	10/10	10/9.3/5.8/25.1
System No. 21	10/10	10/9.2	10/4.4	10/3.7	10/3.7/4.3/18.1
FBE-A	10/10	10/10	10/10	10/10	10/10/1.3/21.3
FBE-B	10/10	10/5.7	10/4	10/3.8	10/4/3.5/17.5
FBE-C	10/10	10/10	10/10	10/10	10/10/3.3/23.3
FBE-D	10/8.2	10/4	10/6.7	10/3.7	10/2/0/12

Table 4. Cathodic Disbondment Test Results (4).

Coating System	Panel Number	Radius (mm)	Average Radius (mm)
System No. 6	17	16.2	16.2
System No. 6	18	16.2	
System No. 6	19	16.2	
System No. 21	31	9.5	12.2
System No. 21	32	14.3	
System No. 21	34	12.7	
FBE-A	A-24	12.7	12.7
FBE-A	A-25	12.7	
FBE-A	A-26	12.7	
FBE-B	B-16	19.8	19.3
FBE-B	B-17	19.1	
FBE-B	B-18	19.1	
FBE-C	C-2	11.1	12.2
FBE-C	C-3	12.7	
FBE-C	C-4	12.7	
FBE-D	D-38	22.2	24.3
FBE-D	D-39	22.2	
FBE-D	D-40	28.6	

The cathodic disbondment test results (4) are displayed in Table 4. This table shows that epoxy polyamide and the FBE A and C coatings display approximately the same amount of resistance to corrosion in the susceptible areas of a given coating system. With that being said, the results of this test alone should not be utilized to draw a final conclusion regarding the performance of a coating system. Instead, a correlation should be made (if possible) between this test and other tests performed, such as immersion and cyclic corrosion tests, to determine more concrete conclusions. In this case, a correlation can be drawn for the FBE D coating as it performed the worst in the cathodic disbondment, immersion, and cyclic corrosion tests.

The final test results (4), which were the impact resistance tests, are documented in Table 5. After reviewing the results, it is apparent that all of the FBE coatings are superior with respect to this specific quality. Since the coated structures are susceptible to damage during transport or installation and this damage may lead to premature breakdown of the coating system, this beneficial performance trait is important because the FBE coated structures may be less susceptible to early corrosion. This quality would lead to better long term performance.

Table 5. Impact Resistance Test Results (4).

Coating System	Inch-pounds	Joules
System No. 6	70	7.9
System No. 21	125	14.2
FBE-A	>160	>18.1
FBE-B	>160	>18.1
FBE-C	>160	>18.1
FBE-D	>160	>18.1

When all of the results (4) from this testing is compiled and compared, there are some preliminary conclusions regarding the FBE coatings. First, the long-term corrosion resistance of the FBE A, B, and C coatings, when exposed to the immersion and cyclic corrosion tests, was relatively consistent when compared to the performance of the epoxy polyamide and coal tar epoxy coatings. Therefore, the FBE coatings may be more capable of providing corrosion protection in a variety of situations. While the FBE coatings may provide this flexible capability, there is some concern due to the high amount of heat required to apply the coating. This preparation may be very costly to perform in the field which would necessitate shop preparation for every item to be coated. Next, the performance of the FBE D coating was poor with respect to the long-term corrosion resistance and cathodic disbondment test results. Therefore, a correlation was established between the poor performance in both of those categories for the FBE D coating. Furthermore, another correlation can be made between coating thickness displayed in Table 6 and long-term corrosion resistance for the FBE coatings. Since the FBE D coating performed the worst for this type of coating throughout the testing and its coating thickness is significantly smaller than the other three FBE coatings, it appears that the dry film coating thickness has a direct impact on the long-term corrosion

resistance properties of FBE coatings. In addition, the film thickness also seems to have some impact on the method of coating failure. When reviewing the summarized results for blistering and undercutting in Tables 1, 2, and 3, the coatings with the thicker films, which were the coal tar epoxy (system No. 6) and the FBE A and C coatings, received much higher scores in these performance categories across the board. Finally, the FBE coatings were superior to the control coatings in the impact resistance testing. This suggests that FBE coatings could provide better long-term corrosion protection as they appear to be less susceptible to damage from impact during transport or installation.

Table 6. Average Dry Film Coating Thickness (4).

Coating System	Average Dry Film Coating Thickness (0.001 in)
System No. 6	22.1
System No. 21	6.5
FBE-A	16.2
FBE-B	17.6
FBE-C	16.6
FBE-D	7.2

3-Moisture Cured Urethane Coatings

3.1-Background

Moisture Cured Urethane coatings (5), or MCU coatings, were initially formulated in Germany. In the 1980's, the United States began their use this coating product. According the Federal Highway Administration (FHWA), "the special characteristics of the coating systems are reported to be attributed to the excellent resin properties of the urethanes and the inclusion of micaceous iron oxide (MIO) with a lamellar crystalline structure...This type of MIO structure enhances shielding of UV light, provides good abrasion resistance, and retards the penetration of moisture, oxygen, and other corrosive substances to steel surfaces."¹⁹ The binder utilized in this coating system is called isocyanate. In contrast to the FBE coatings, this system does not utilize a curing agent to form the coating film on the metal substrate surface. In fact, the isocyanates form "high-molecular-weight polyureas by reacting with moisture in air."²⁰ Since this particular resin is very reactive with the environment, special care should be taken to ensure that application equipment is dry as well as maintaining a good seal on the containers when the material is placed into a storage condition. Some of the advantages provided by this coating system include "a single package, longer pot life, fast topcoating, and low temperature and high humidity applications."²¹ The typical commercial uses for this product include overcoating of steel bridges, which are in close proximity to the marine and/or humid environments.

3.2-Performance

The FHWA (5) conducted a testing set on three specific formulations of MCU coatings. All of these coating systems utilized in this testing were well below the EPA mandated VOC limit for architectural coatings. These systems were applied to surfaces, which were prepared by the SSPC SP 10 and SP 3 specifications, according the existing manufacturer instructions. Table 7 displays the coatings utilized for the SSPC SP 10 prepared surfaces. In addition to the typical application process, a separate set of test

Table 7. MCU Coating Systems (SSPC SP 10 Surfaces) (5).

<u>System</u>	<u>Coating System</u>	<u>VOC, g/L</u>
A	Zinc-rich urethane/MIO ^a -filled urethane/urethane	314/315/314
B	Zinc-rich urethane/MIO-filled urethane/MIO-urethane	336/336/336
C	Zinc-rich urethane/MIO & Al ^b -filled urethane/MIO-filled urethane	337/340/336

^a Micaceous iron oxide.

^b Aluminum.

sample surfaces were contaminated with an evenly dispersed 20 µg/cm² chloride solution prior to the application. Subsequently, a two inch scribe was added to the coating according to ASTM standards. An additional application of urethane sealer was utilized prior to application of the coating systems displayed in Table 8 for the SSPC SP 3 prepared surfaces. All of these coating systems were evaluated in laboratory conditions

Table 8. MCU Coating Systems (SSPC-SP 3 Surfaces) (5).

<u>System Code</u>	<u>Coating System</u>	<u>VOL, g/L</u>
A1	MIO ^a & Al ^b filled urethane/MIO-filled urethane/urethane	315/315/314
B1	Zn ^c & MIO-filled urethane/MIO-filled urethane/MIO-filled urethane	336/336/336
C1	MIO & Al-filled urethane/MIO & Al-filled Urethane/MIO-filled urethane	340/340/336

^a Micaceous iron oxide.

^b Aluminum.

^c Zinc.

as well as an outdoor environment. The testing period consisted of a total of 4000 hours with examination and measurements of rusting, blistering, and scribe creepage (undercutting) occurring at 500 hour intervals. The laboratory testing included a cyclic freeze/UV-condensation/Prohesion method. Since this ASTM standard was slightly modified, Tables 9 and 10 are provided to provide actual conditions. The outdoor conditions indicated in Table 10 represent an FHWA testing site in Sea Isle, NJ. The test samples at this site were exposed to natural sea water spray and examined at the same frequency as the lab samples. In addition to this corrosion resistance testing, film thickness, hardness, and adhesion strength values were determined.

Table 9. Laboratory Test Conditions (5).

Every 500-h cycle included the following tests:

1. Freeze: 68 h
Temperature: -23°C (-10 °F)
2. UV-Condensation: 216 h (9 days)
Test cycle: 4-h UV/4-h condensation cycle
UV lamp: UVA-340
UV temperature: 60 °C (140 °F)
Condensation temperature: 40 °C (104 °F)
Condensation humidity: 100% relative humidity
3. Prohesion (cyclic salt-fog, ASTM G85): 216 h (9 days)
Test cycle: 1-h wet/1-h dry
Wet cycle: A Harrison Mixture of 0.35 wt% ammonium sulfate and 0.05 wt% sodium chloride was used. Fog was introduced at ambient temperature.
Dry cycle: Air was preheated to 35 °C (95 °F) and then was purged to the test chamber.

Table 10. Outdoor Test Conditions (5).

Sunshine: 2,840 h
Relatively humidity: 70%
Time of wetness: 51%
Rainfall: 150 cm
pH of rain water: 4.2
Conductivity of rain water: 163 $\mu\text{S}/\text{cm}^*$
Composition of rain water: 27 ppm Cl^- , 25 ppm SO_4^{2-}
Water temperature: 9.1 °C (48.4 °F)
Spray seawater:
pH = 7.5
Salt content: 2.7 wt%

* Microsiemens per centimeter.

The results of the FHWA study (5) are summarized for the MCU coatings in order to provide some important characteristics. First, these coatings provide the user with strong mechanical properties, which include hardness and adhesion strength for both the SSPC SP 10 and SP 3 prepared metal substrate surfaces. In addition, these coatings provide excellent barrier qualities because there were no coating surface failures for the duration of the testing. However, the intentionally scribed portions of all samples

exhibited varying levels of undercutting (scribe creepage). The level for the SSPC SP 10 prepared samples was greater for the surfaces that were contaminated with the chloride solution. The chloride solution did not have a substantial effect on the SSPC SP 3 prepared surfaces. While the effect of this contamination was negligible for the SSPC SP 3 surfaces, the coating applications, in which the sealer was used, exhibited more undercutting than the coating system without the sealer. Next, this undercutting, which occurred at a linear rate during the testing, is determined by primer properties such as corrosion resistance, primer type, and the metal substrate surface conditions. In addition, the particle size distribution in each one of the coating layers (primer, midcoat, and topcoat) plays a key role in coating performance. The FHWA states "...zinc particle size distribution played a more important role in primer performance on SSPC SP 10 surfaces than did the amount of zinc. Too much large pigment particles reduced the coating performance of the MC-urethanes over both SSPC SP 10 and SSPC SP 3 steel surfaces. It seems critical to have a proper size gradation for pigment particles with a sufficient amount of high-grade small particles in order to achieve good coating performance. A minimum amount of small particles should be included in the formulation and is recommended as a key element in the coating specifications."²² The chemical composition of the coating system also has a direct impact on the performance. According to the FHWA, "these variables included the ratio of the aromatic content to the aliphatic content of MC-urethanes, the ratio of the pigment content to the binder content, and the elemental content of the pigment and other factors."²³ Finally, the total coating thickness is very important to ensure effective performance of the coating and should be a minimum of 225 μm .

In addition to the FHWA's study, the Naval Facilities Engineering Service Center (NFESC) in Port Hueneme, CA has published one technical memorandum with another under review regarding the performance of MCU coating systems. The first study (6), which was performed to ascertain the feasibility of the use of the MCU coatings on antenna towers, consisted of a site visit to two Oregon Department of Transportation (DOT) bridges utilizing the MCU coatings and some specific experiments with MCU coatings provided by the industry. The site visits included the Astoria Bridge located over the Columbia River, which was coated in 1993, and the Manzanita Bridge, which is located one mile from the coast and was coated four years earlier than the Astoria Bridge. These bridges were examined for coating surface failures, degree of corrosion, and reduction in gloss.

The other portion consisted of specific testing (6) performed on eight different formulations of MCU coatings. The test samples were prepared by utilizing solvents to wash the metal substrate followed by abrasive blasting to a white metal finish. The first test included the application of each coating to a wet surface in order to determine any significant difference in strength between coating a dry and wet surface. This test utilized de-ionized water as the substance to contaminate the surface prior to application. Next, a Bio RadTM Fourier Transform Infrared Spectrometer (FTIR) was employed to determine the chemical composition of the topcoats within each coating system. NFESC also performed ASTM adhesion testing similar to the FHWA on each test sample to determine bonding strength. Another similar test between the FHWA and NFESC was a weathering test where the conditions utilized by NFESC were different. The testing, which was done to determine the ability of the topcoat to retain its gloss, color, and

corrosion resistance, was conducted for a total of 3000 hours and consisted of two distinct weather conditions. The first condition included exposure to UV light (140°F) on alternating basis with a water spray and no UV light. The other was continuous exposure to UV light. In order to assess the color retention of a specific coating, a Perkin Elmer™ UV/VIS Spectrophotometer was used. The gloss retention for each coating was evaluated before and after the UV exposure through the use of a Gardco® micro-TRI-gloss. The final performed test was the application of a MCU coating with zinc-rich primer by synthetic mitt and brush on horizontal and vertical surfaces to assess the ability of the coating to achieve a uniform thickness within manufacturer standards. In order to make that coating thickness evaluation, an Elcometer™ Model 345 Magnetic Gauge was utilized after coating and a sufficient amount of drying time.

The following is a summary of the findings by NFESC (6) after this round of testing. First, there were no significant deteriorations in the coatings on either of the Oregon DOT bridges, which had been exposed for numerous years prior to the site visit. Next, the MCU coatings develop acceptable bonding strengths to a wet substrate when the coating system adequately displaces the majority of the wet substance preventing the bond. In addition, the MCU coatings develop excellent bonding strengths when they are applied to abrasively blasted metal substrates or to MCU intercoats. However, the aliphatic MCU topcoats experienced a reduction in their gloss and color after exposure to the simulated weathering conditions. The use of the synthetic mitt and brush may provide coating thicknesses for the MCU coatings that are not within the manufacturer guidelines. Therefore, these application methods would require more quality control to ensure the guidelines are met. Next, the Relative Humidity (RH) plays an important role in the curing mechanism of these coatings. Specifically, RH values below 30% may create curing times which are too slow and do not meet manufacturer standards while values of 83% may develop times that are too fast. In addition, the use of xylene as a solvent for the MCU coating system may produce unacceptable bubbling if the coating thickness exceeds 3 mils. When the two component aliphatic urethanes are compared to topcoats utilizing only aliphatic resins, the two component aliphatic urethanes provide a higher resistance to UV light. Finally, NFESC concluded that MCU coatings should always be tested prior to field use as all designs do not provide the same excellent corrosion resistance properties.

The second NFESC performed study (7) was a Demonstration and Validation (DEMVAL). This particular DEMVAL was conducted to assess the performance of MCU coatings for an exterior metal substrate. It consisted of a contractor application of the MCU coating to a water tank at the Naval Weapon Station Seal Beach in California, the monitoring of the procedures utilized, a follow up inspection of the site after one year, and the development of Uniform Facility Guide Specifications (UFGSs). Since the water tank was coated with Lead Based Paint (LBP), the removal strictly followed all applicable guidelines for LBP removal. Subsequent to this removal, the metal surfaces were tested for any type of non-visible contamination. Then, the metal substrate was prepared for the coating application by abrasive blasting. The contractor proceeded with the application of the coating system according to the manufacturer guidelines. During application, there were some inconsistencies (film thickness was too thick in a few areas) and a few areas of minor damage to the coating (due to scratches by scaffolding or

rubbing by equipment hoses). These discrepancies were remedied under the supervision of NFESC with no detrimental effects to the coating system.

The second study (7) produced the following conclusions. First, the MCU coating procedure does not include any specially procured equipment as the application can be accomplished by conventional airless spray or brush/roller technology. In addition, there are no special safety precautions to be followed as the typical hazards only include the high pressures with the spray equipment and the displacement of air by the high concentration of VOCs in close proximity to the surface being coated. There are also no special inspection techniques to be performed during the application procedures. If there are any discrepancies discovered subsequent to the application, the procedures to correct them are comparable to any other commercially available industrial coating. Therefore, the MCU coatings can be classified as a typical industrial coating in current practice. Next, SSPC SP 10 must be utilized to prepare the metal substrate surface if zinc-rich primers will be utilized in the coating system. The aliphatic MCU coatings are also more resistant to UV light than epoxy or alkyd coatings even though they may not be as effective as two component aliphatic urethanes. Finally, NFESC recommends that additional monitoring should be performed before wide use as the long term performance has not been documented for the MCU coatings.

4-Epoxy Aliphatic Polyurethane with Polypropylene Fiber Coatings

4.1-Background

The next coating system includes an epoxy coat as the primer on the given metal substrate and a topcoat consisting of aliphatic polyurethane with polypropylene fibers. In some of the formulations of the two previously discussed coating systems, aliphatic polyurethanes were utilized. However, the addition of the polypropylene fibers (8) to this topcoat formulation could provide some additional strength as one of the primary properties of polypropylene is its very good resistance to fatigue. Specifically, this quality may provide some additional reinforcement to the bonding strength of the polyurethane topcoat. Another beneficial quality of the polypropylene is that pigments can be added to the mixture to produce it in many different colors. Since coating formulations are found in a variety of colors, this quality is very beneficial for the end user. However, this product is not very resistant to UV light exposure and needs specific additives to provide this lacking feature. While the coating system has some potentially good qualities that may serve it well in the industrial setting, testing must be accomplished to quantify performance.

5-Glass Flake Resin Coatings

5.1-Background

There was not an adequate amount of information to determine the makeup (primer, midcoat, topcoat) of this particular coating system. In addition, there has not been any study on the performance of this coating in the industrial environment. Therefore, no conclusions can be made regarding the potential for its use on waterfront structures at this time.

6-Summary and Conclusions

In general, the FBE coatings performed relatively well when compared to the epoxy polyamide and the coal tar epoxy coatings. In fact, there is some preliminary evidence which suggests that the FBE coatings may be suitable for protection from corrosion in a wider variety of environmental conditions. This level of resistance seems to be related to the coating thickness for a given formulation of the coating system. In addition, there are some results that indicate that FBE coatings may be more resistant to damage during installation or shipment. This impact resistance could result in better long term performance when compared to the current coatings in use at this time. Since the coatings in use do not meet the current VOC requirements of the EPA, these two beneficial results warrant more study from the Navy on the topic of FBE coatings. All of the specific formulations of the FBE coatings should be tested prior to use in the marine environment.

The studies performed on MCU coatings are not as conclusive because the testing was only performed on the coating and no comparison to the epoxy polyamide or coal tar epoxy coatings was made. Although no comparisons were made, there are some important characteristics to be mentioned. First, the MCU provide good corrosion resistance properties to the metal substrate surface. In addition, the coating possesses good mechanical qualities, which include hardness and adhesion strength. The actual performance of the MCU coatings is dependent on many typical factors. Some of these factors include the surface conditions, coating thickness, atmospheric conditions, and chemical composition. Finally, the MCU coating systems do not require specially procured application or safety equipment which would keep the costs at a relatively smaller level. Since there were no performance comparisons made to the current coatings in use, these tests should be performed. In addition, the formulations of the MCU coatings should always be tested prior to field use to establish base performance data.

In general, there definitely needs to be additional testing performed on all of the potential coating systems as some of the coatings have received no independent study thus far. This testing will provide a more comprehensive database of information in order to make better recommendations on coating use in the harsh marine environment. As this environment is very harsh, special attention should be paid towards the study of the impact resistance of each coating because these structural members are definitely susceptible to damage in transit or during installation. In addition, the testing should include outdoor and laboratory (simulated) exposure to the marine environment in order to make comparisons between lab and outdoor exposure results. As the EPA has set the new limits for VOC in architectural coatings, this testing should include VOC testing to ensure that all formulations meet the current standards. Finally, the testing should be standardized such that each substrate is prepared according to current SSPC standards and all quality control standards are met for the coating application procedures.

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